

SURVEY OF PLASMA DIAGNOSTIC TECHNIQUES APPLICABLE TO RADIOGRAPHIC DIODES *

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Abstract

Plasmas are ubiquitous in the high-power electron beam diodes used for radiographic applications. In rod pinch and immersed B_z diodes they are found adjacent to the cathode and anode electrodes, and are suspected of affecting the diodes' impedance characteristics as well as the radiographic spot size. In paraxial diodes, preionized plasmas or beam-formed plasmas are also found in the gas focusing section. A common feature of the plasmas adjacent to the electrodes is that their densities can range from 10^{12} - 10^{17} cm⁻³, and their velocity is on the order of 10^7 cm/s. Researchers from the Naval Research Laboratory have developed a high-sensitivity two-color interferometer that is presently being tested on Gamble II for future use on the Sandia RITS accelerator operating with a B_z diode. This diagnostic is capable of resolving a line-integrated electron density of 2×10^{12} cm⁻², a density that might be capable of even observing the electron beam directly. This paper will present an overview of laser-based and spectroscopic diagnostics that could be used to measure plasmas found in radiographic diodes with spatial and temporal resolutions on the order of 1-5 mm and 5 ns, respectively. Plans for the use of this diagnostic on a preionized plasma cell of a paraxial diode on the Sandia RITS experiment will be discussed.

I. INTRODUCTION

High intensity pulsed power-driven electron beams are used to create bremsstrahlung x-ray sources for flash radiographic imaging of dynamic experiments [1]. Whereas typical industrially available sources operate below 200 GW/cm² intensities, experimental requirements exceed 50 TW/cm² intensities. Progress in improving source brightness requires a better understanding of power flow in magnetically insulated transmission lines (MITL's), coupling of the power flow to the electron beam diode load, and the impedance behavior of the diode. To a large extent the LSP code [2] has been successful in simulating the complex particle and field dynamics found in the various stages of power flow in these sources. In particular, LSP simulations have suggested physical explanations for the impedance behavior of the various diodes used. In order to gain a deeper understanding of the impedance behavior of radiographic diodes it would be important to experimentally measure plasma evolution and motion *in-situ*. This paper surveys plasma diagnostic techniques that could be employed in measuring electron densities in the vicinity of radiographic diodes. Furthermore, plans to diagnose a preionized plasma cell of a paraxial diode utilizing a two-color interferometer (and its variants) developed by researchers at the Naval Research

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Laboratory [3] that will be fielded on the Sandia RITS experiment will be described.

II. PLASMA DIAGNOSTICS IN PULSED POWER EXPERIMENTS

A. Historical Overview

Plasma diagnostics refers to the observation of physical processes that allow one to infer parameters that characterize a plasma [4]. It had its inception in the late nineteenth century with the observation of colored glows from gas-filled discharge tubes. These plasmas were low temperature and weakly ionized.

The emergence of controlled thermonuclear fusion research in the 1950's spawned new interest in the subject. The high temperatures and densities of fusion-relevant plasmas required the development of new nonintrusive diagnostics. The accompanying development of lasers and sensitive solid-state detectors made possible new diagnostic techniques and the application of existing techniques to the new parameter regimes [5].

The requirements for semiconductor manufacturing caused a resurgence of interest in glow discharge plasmas in the late 1980's. These plasmas are low temperature and weakly ionized, in contrast with their fusion counterparts. The materials processing community is now utilizing many of the plasma diagnostic techniques that were advanced by research in controlled fusion.

Recently, the plasma diagnostics community has been challenged by the need to characterize the plasmas associated with research into high energy density plasmas [6]. These include the strongly coupled plasmas produced in laser-driven inertial confinement fusion experiments and pulsed power-driven Z-pinch sources, as well as the intentional and unintentional plasmas associated with pulsed power experiments.

B. Plasma Diagnostics for Pulsed Power Experiments

The challenges of diagnosing intentional and unintentional plasmas associated with pulsed power experiments include: the presence of very large electric and magnetic fields; the presence of various ion species, charge states, and neutrals; the change in these parameters over nanosecond time scales; and the notoriously inadequate access to the plasmas. The large electron densities and typically small spatial extent of electron sheaths in pulsed power experiments leave only two techniques that could be exploited: laser interferometry and spectroscopy. (It should be mentioned that Thomson Backscattering has been successfully used to determine the axial momentum spread of a pulsed power-driven relativistic electron beam [7]. The plasma in this case was the electron beam itself, and in this paper we concern ourselves with plasmas other than the electron beam in a radiographic diode.)

1) Laser Interferometry in Pulsed Power Experiments

Among the first to utilize interferometry in a pulsed power experiment was an effort at Sandia National Laboratories to measure free-electron line densities and anode/cathode plasma motion in a magnetically insulated ion diode utilizing pulsed ruby laser holography [8]. The goal of that effort was to better understand impedance collapse and how neutrals contribute to it. This is an example of attempting to characterize unintentional plasmas in pulsed power. Subsequently, a group at the Naval Research Laboratory utilized heterodyne-phase-detection helium-neon (HeNe) laser interferometry in a plasma opening switch [9] to characterize the dynamic evolution of an intentionally introduced plasma during the conduction phase of the switch. Line densities of the order 10^{16} - 10^{17} cm⁻² were measured in that experiment.

Researchers at Los Alamos National Laboratory utilized visible and infrared laser interferometry to probe the time history of line-integrated electron density at several axial positions across the anode-cathode (*A-K*) gap region of a magnetically insulated ion diode [10]. Line densities on the order of 10^{16} - 10^{17} cm⁻² were measured. The conclusion of that work was that electron density was observed to build up in two phases, where the larger second phase was attributed to ion beam impact of the cathode structure.

Researchers at the University of New Mexico utilized a HeNe laser in a two-pass interferometer configuration to characterize the build-up of unintentional plasma in the slow wave structure of an intense relativistic electron beam-driven backward wave oscillator [11]. In this study electrons were found to build-up in two phases, with the second phase being attributed to a microwave discharge occurring in the slow wave structure, which was suspected of quenching the absolute instability responsible for the generation of microwaves. Line-integrated electron densities in this measurement were comparable with those measured in earlier interferometry experiments in pulsed power devices.

Finally, in a series of experiments and developmental efforts that continues through the present, researchers at the Naval Research Laboratory have been utilizing a sensitive two-color interferometer to characterize pulsed power plasmas [12-14]. Most recently [15], a reconfigured two-color interferometer is being prepared by the Naval Research Laboratory for use on the Sandia National Laboratories' RITS experiment. Measurable line-integrated electron densities of 2×10^{12} cm⁻² (corresponding to a phase change of 10^{-5} waves, or an optical path change of 10^{-11} m) waves are anticipated with this tool. We will return to this interferometer in Sec. IV of this paper.

2) Spectroscopy in Pulsed Power Experiments

Although the researchers in [8] complemented their pulsed ruby laser holographic measurement of electron densities with an ultraviolet spectroscopic inference of electron temperature, arguably the first comprehensive use of spectroscopy in pulsed power was the measurement

of anode plasma density in a magnetically insulated diode by a group at Cornell University [16]. In this work, the Stark broadening of the neutral hydrogen H_β line yielded information regarding the average electron density and its temporal evolution. Electron densities of about $2 \times 10^{15} \text{ cm}^{-3}$ were measured.

The most comprehensive development of the spectroscopic characterization of pulsed power plasmas has occurred at the Weizmann Institute of Science in collaboration with several other groups over the years. Since the mid-1980's, this group has developed analysis tools to interpret measurements performed in vacuum gaps, in plasma opening switches, as well as other aspects of pulsed power experiments. Representative elements of this body of work can be found in [17-21]. A major challenge in the use of spectroscopic techniques in pulsed power experiments is the interpretation of the data, which often requires significant modeling to complement the data acquisition.

III. Z-DISCHARGE PLASMA SOURCE FOR A PARAXIAL DIODE

Motivation for this paper was partly the interest in generating a fully ionized plasma cell for use in a paraxial diode for radiographic applications. A 10^{15} - 10^{16} cm^{-3} density plasma in the transport cell is predicted to be sufficient to ballistically transport the beam. Plans are to use a Z-discharge source, in its quiescent afterglow stage, to generate the plasma. LSP hybrid simulations suggests that plasma conductivity $\sigma > 10^{14} \text{ s}^{-1}$ for a singly ionized 3 eV plasma with $\nu = 10^{10} \text{ s}^{-1}$ if collisionality is classical.

Plans are to use a static prefill of H_2 or He, 200 – 300 mTorr and strike a low voltage ($< 10 \text{ kV}$) ringing discharge to generate the plasma. The proposed schematic of this experiment is shown in Fig. 1.

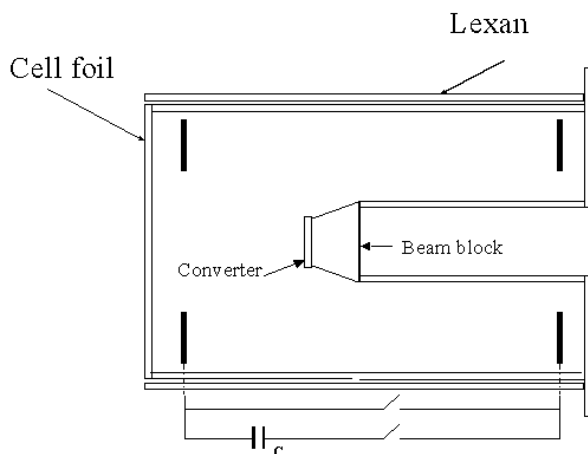


Figure 1. Schematic of a proposed Z-discharge plasma cell for a paraxial diode.

The high sensitivity two-color interferometer developed by the Naval Research Laboratory will be employed to characterize the plasma cell for use on the paraxial diode

on the RITS experiment at Sandia National Laboratories. Additionally, a heterodyne interferometer may be useful to determine the spatial uniformity and density more accurately, measuring line densities $\sim 5 \times 10^{15} \text{ cm}^{-1}$ and above. Although this technique has a longer time response (~ 15 -20 ns), this should not be a problem for this type of discharge.

IV. SUMMARY

In this paper we have presented a survey of plasma diagnostics as it pertains to pulsed power plasmas. Because of the high electron densities, and small spatial extent of typical plasmas, laser interferometry and spectroscopy are the most relevant techniques. Plans for the use of a Z-discharge plasma cell in a radiographic diode motivated aspects of this work.

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